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A Novel SFG Structure for C-T Highpass Filters

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Abstract

This paper presents the design of a sixth order elliptic highpass filter having a passband frequency of 3.0KHz, a passband ripple of 1.0dB and a stopband attenuation of 50dB. The filter is based on a novel integrator based SFG describing a passive prototype filter; this SFG is simulated using MOSFET-C building blocks. The noise performance is considerably enhanced when compared to other highpass filter structures. Well within the stopband the output noise is dominated by amplifier noise, but only one amplifier contributes and its equivalent input noise is simply copied to the output (not amplified). Around the passband frequency MOSFET-resistor noise is the dominant noise source, but the number of MOSFET-resistors is kept at a minimum, thus reducing this noise source. The above mentioned noise properties are directly related to the new filter structure, which in addition to this has the advantage of being quite simple when compared to other integrator based highpass filter structures.

I. Introduction

The design of higher order lowpass filters is most frequently based on the leapfrog method [1] for simulating passive prototype filters since this yields circuits with low sensitivities to parameter variations. If the leapfrog method is used for the design of highpass filters, then differentiators are required. However differentiators are very difficult to implement with a large frequency range while maintaining stability. For this reason an integrator based structure for implementing highpass filters would be convenient, since integrators generally have very good high frequency and stability properties.

The Direct SFG Simulation method presented in [2] provides such an integrator based highpass filter structure, but unfortunately it becomes very complex with higher order filters. An alternative integrator based highpass filter structure, which will be referred to as the New Active Ladder method, was introduced by the author in [3]. With this new structure, the better properties of the leapfrog method (simplicity and regularity) and the Direct SFG Simulation method (integrator based) are combined into a new powerful highpass (and bandstop) filter structure.

This paper will describe in more detail the design of a sixth order elliptic highpass filter based on the SFG structure described in [3]. The circuit uses MOSFET-C integrators [4] and has been fabricated in a 2.4 μ m double-poly double-metal CMOS-process. A serious problem with implementing continuous-time filters (especially for low frequencies) is that large capacitance-values are impractical [5], e.g. in the used process a capacitor of 1.0pF takes up approximately 3000 μ m². For this reason resistor-values must be relatively high leading to large noise-voltages, and with many integrated resistor implementations the parasitic capacitance can become important. If e.g. N-channel MOSFET's having a channel width of W and a gate bias voltage V_C are used for resistors R then the parasitic capacitance C_τ will be

$$C_\tau = C_{ox}WL = C_{ox}W R \mu C_{ox} W (V_C - V_T) = \mu (C_{ox}W)^2 (V_C - V_T) R$$

The used technology gives $C_\tau=1.2$ pF for $R=2$ M Ω . Especially for voice-band applications this effect has to be considered.

II. Filter structure

It is a well known fact that filter structures based on doubly terminated LC-ladder filters exhibit low sensitivities to parameter variations within the passband [1]¹. The filter structure described in this paper is such an LC-ladder based structure. The sixth order prototype filter of Fig. 1 can be modeled using the New Active Ladder method and this yields the SFG of Fig. 2. The solid line branches form the basic highpass SFG and the 'cross-coupling' branches (dashed lines) generate the non-zero transmission zeros of the elliptic transfer function. As is the case with leapfrog filters, node voltages and series currents are chosen for state variables. Not all branches of this SFG are integrating, in fact all the nodes have constant-gain input branches. However this is not a problem, since this can be achieved by feeding capacitively the summing node of a standard Miller integrator [4].

The alternative SFG based on the Direct SFG Simulation method is shown in Fig. 3. Two of the state variables (I_{L2} and I_{L4}) and the connected branches (dashed lines) are not present in a basic highpass SFG, they form the non-zero transmission zeros of the elliptic transfer function. In an active implementation of this SFG, one operational amplifier per state variable is needed, and hence four extra amplifiers are required, when compared to the New Active Ladder structure. Furthermore the integrating nodes have several inputs; if this is accomplished simply by connecting several input resistors to the summing node of the same Miller integrator, then more noise will be present at the output. The equivalent output noise V_{NO} of a Miller integrator having N inputs, time-constants RC and equivalent amplifier input noise V_{NA} is:

$$\overline{V_{NO}^2} = \frac{1}{(\omega C)^2} \left(N \frac{4kT}{R} + N^2 \frac{V_{NA}^2}{R^2} \right)$$

Clearly, if integrator noise is to be minimized, then the number of inputs should be small.

III. Comparison of filter structures

Two filter circuits using scaled versions of the SFG's of Fig. 2 and Fig. 3 have been designed and simulated. In order to get a fair comparison, both circuits have been designed to have a total filter capacitance of 500pF, and this capacitance is equally distributed among the integrators. Both circuits have been optimized to cancel out the effect of resistor-parasitics; using numerical optimization the values of

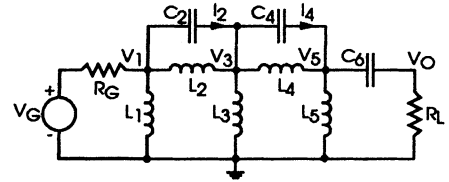


Fig. 1 Sixth order elliptic highpass ladder.

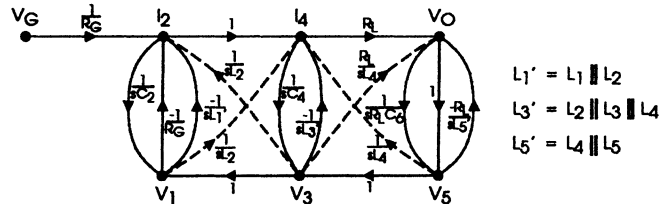


Fig. 2 New Active Ladder signal flow graph describing a sixth order elliptic highpass filter.

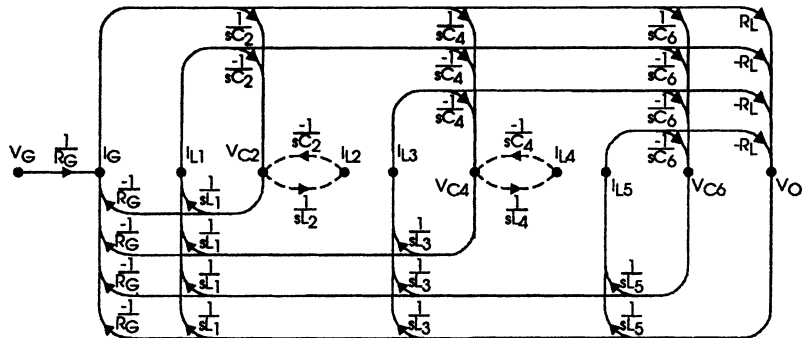


Fig. 3 Signal flow graph based on the Direct Simulation method.

¹ The low sensitivity property is only valid for *real* variations; the conclusion is based on the assumption that the LC-ladder is lossless. Imaginary deviations (phase errors) can in fact cause serious errors.

selected components were adjusted to minimize the error of the transfer function. The simulations are performed using SPICE taking parasitic resistor-capacitances, amplifier bandwidth (5MHz) and amplifier noise ($20\text{nVHz}^{-1/2}$, noise corner 200KHz) into account.

Fig. 4 shows the simulated gain-responses. The deviation at very low frequencies is due to the fact that the Direct SFG Simulation circuit is very sensitive to resistor-parasitics in the stopband [3].

Fig. 5 shows the simulated noise performance of the two filter circuits and the operational amplifier used in the circuits. The New Active Ladder circuit clearly has the best noise performance. In the passband its output noise density is 2.5-4.5dB below that of the Direct SFG Simulation circuit, and the total output noise of the frequency band 3-100KHz is $150\mu\text{Vrms}$ versus $215\mu\text{Vrms}$ for the Direct SFG Simulation circuit.

In the stopband where amplifier noise is the dominant noise source, the New Active Ladder circuit has up to 20dB less output noise. In the New Active Ladder circuit (Fig. 6) the low frequency noise is dominated by the V_5 integrator; the equivalent input noise is copied to the output. In the Direct SFG Simulation circuit (not shown) output noise is dominated by the opamp's of the V_O summing amplifier and the V_{C6} integrator; in both cases the opamp noise is amplified, so the output noise becomes much larger than the opamp noise.

IV. Circuit implementation

The schematic of the highpass filter circuit is shown in Fig. 6 and a chip-photograph is shown in Fig. 7. The opamp is a two stage design with automatic balancing of the differential output [6]. The MOSFET-resistors have been implemented using unit-size P-channel devices with $L=36\mu\text{m}$ and $W=3.6\mu\text{m}$. With a nominal gate voltage $V_C=-3.5\text{V}$ and bulk voltage $V_B=5.0\text{V}$, each unit device has a resistance of $313\text{K}\Omega$ and a total channel capacitance of 0.165pF . The capacitors have been implemented using the two polysilicon layers; here unit-capacitors of 1.0pF were used.

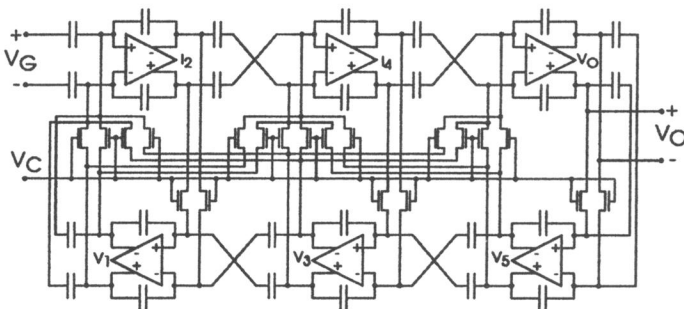


Fig. 6 Schematic of the New Active Ladder sixth order highpass filter. V_C is the control voltage, V_O is the input and V_O is the output.

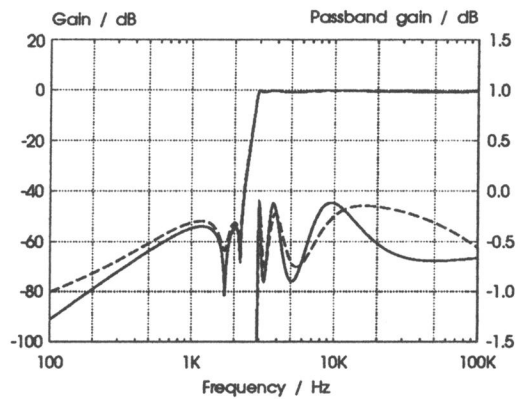


Fig. 4 Simulated amplitude responses of New Active Ladder circuit (solid) and Direct SFG Simulation circuit (dashed).

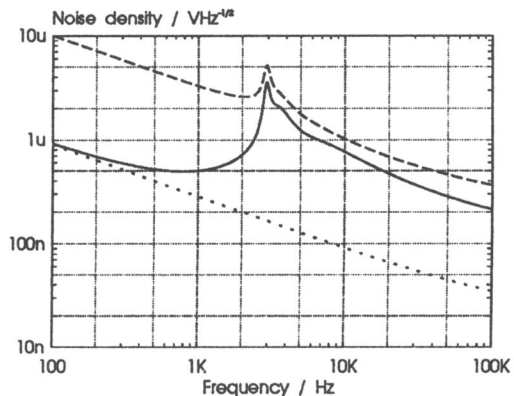


Fig. 5 Simulated noise spectrum of New Active Ladder circuit (solid), Direct SFG Simulation circuit (dashed) and opamp (dotted).

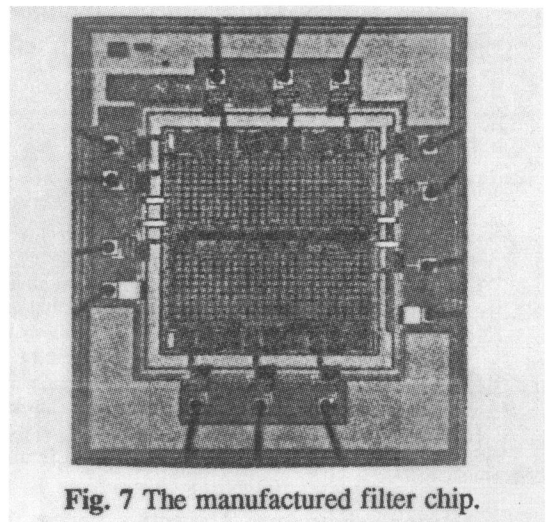


Fig. 7 The manufactured filter chip.

V. Measured results

The manufactured filter chip was found to be functional, and after adjusting the control-voltage V_G , the gain response of Fig. 8 was measured. This response is very close to the simulated response (Fig. 4). The spectrum of the output noise was also measured and the result is shown in Fig. 9. Unfortunately the used spectrum analyzer was not able to make measurements over sufficiently large periods of time and therefore the curve is very unsteady, but still with some resemblance to the simulated noise density (Fig. 5). At low frequencies the measured noise tends to be lower than the simulated noise, but this is probably because the flicker noise of the amplifiers was overestimated in the simulations.

VI. Conclusion

The leapfrog filter structure is not suited for implementing highpass filters. This is because differentiators would be required, and high-quality differentiators are difficult to implement. Therefore integrator based highpass filter structures are useful.

A new integrator based highpass filter structure, the New Active Ladder structure, has been presented and compared to the Direct SFG Simulation method [2]. Simulations of a New Active Ladder circuit and an equivalent Direct SFG Simulation circuit show that the New Active Ladder structure has a significantly enhanced noise performance, especially in the stopband where up to 20dB reduction of the output noise is achieved.

A MOSFET-C filter based on this new structure, which implements a sixth order elliptic highpass function with a passband frequency of 3.0KHz, has been designed and manufactured. Measurements confirm the simulated performance.

The described filter structure is easily modified for use with bandstop filters [3], and possibly a general procedure for simulating LC-ladder filters using integrators with non-integrating inputs can be developed.

VII. References

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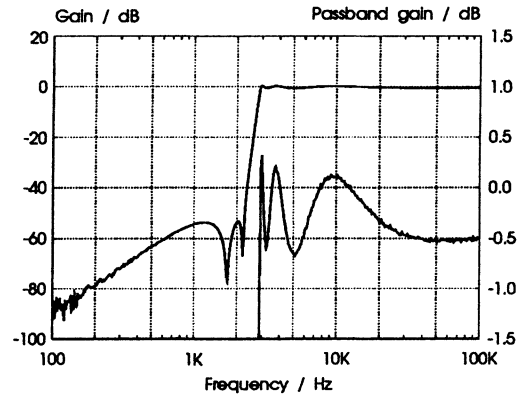


Fig. 8 Measured amplitude response of highpass filter chip.

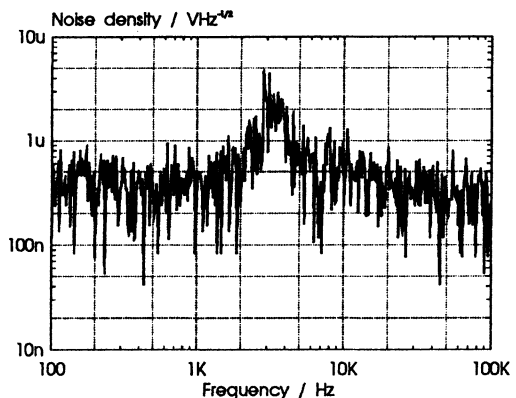


Fig. 9 Measured output noise spectrum of the highpass filter chip.